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Breaking the Biological Barriers to Cellulosic Ethanol:

A Joint Research Agenda

A Report on the Biomass to Biofuels Workshop

December 7–9, 2005

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Executive Summary

"By applying the talent and technology of America, this country can dramatically improve our environment, move beyond a petroleum-based economy, and make our dependence on Middle Eastern oil a thing of the past."

— President George W. Bush, State of the Union Address, January 2006*

A robust fusion of the agricultural, industrial biotechnology, and energy industries can create a new strategic national capability for energy independence and climate protection. In his State of the Union Address (*Bush 2006), President Bush outlined the Advanced Energy Initiative, which seeks to break our national dependence on imported oil by accelerating the development of domestic, renewable alternatives to gasoline and diesel fuels. The president has set a long-term goal of replacing the volume of oil equal to more than 75% of our oil imports from the Middle East by 2025. Fuels derived from cellulosic biomass—the fibrous, woody, and generally inedible portions of plant matter—offer an alternative to conventional energy sources that can dramatically impact national economic growth, national energy security, and environmental goals. Cellulosic biomass is an attractive energy feedstock because it is an abundant, domestic, renewable source that can be converted to liquid transportation fuels. These fuels can be used readily by current-generation vehicles and distributed through the existing transportation-fuel infrastructure.

The Biomass to Biofuels Workshop, held December 7–9, 2005, was convened by the Department of Energy's Office of Biological and Environmental Research in the Office of Science; and the Office of the Biomass Program in the Office of Energy Efficiency and Renewable Energy. The purpose was to define barriers and challenges to a rapid expansion of cellulosic-ethanol production and determine ways to speed solutions through concerted application of modern biology tools as part of a joint research agenda. Although the focus was ethanol, the science applies to additional fuels that include biodiesel and other bioproducts or coproducts having critical roles in any deployment scheme.

The core barrier is cellulosic-biomass recalcitrance to processing to ethanol. Biomass is composed of nature's most ready energy source, sugars, but they are locked in a complex polymer composite exquisitely created to resist biological and chemical degradation. Key to energizing a new biofuel industry based on conversion of cellulose (and hemicelluloses) to ethanol is to understand plant cell-wall chemical and physical structures—how they are synthesized and can be deconstructed. With this knowledge, innovative energy crops—plants specifically designed for industrial processing to biofuel—can be developed concurrently with new biology-based treatment

*www.whitehouse.gov/stateoftheunion/2006/

and conversion methods. Recent advances in science and technological capabilities, especially those from the nascent discipline of systems biology, promise to accelerate and enhance this development. Resulting technologies will create a fundamentally new process and biorefinery paradigm that will enable an efficient and economic industry for converting plant biomass to liquid fuels. These key barriers and suggested research strategies to address them are described in this report.

As technologies mature for accomplishing this task, the technical strategy proceeds through three phases: In the research phase, within 5 years, an understanding of existing feedstocks must be gained to devise sustainable, effective, and economical methods for their harvest, deconstruction, and conversion to ethanol. Research is centered on enzymatic breakdown of cellulosic biomass to component 5- and 6-carbon sugars and lignin, using a combination of thermochemical and biological processes, followed by cofermentation of sugars to specified endproducts such as ethanol. Processes will be integrated and consolidated to reduce costs, improve efficacy, reduce generation of and sensitivity to inhibitors, and improve overall yields and viability in biorefinery environments.

The technology deployment phase, within 10 years, will include creation of a new generation of energy crops with enhanced sustainability, yield, and composition, coupled with processes for simultaneous breakdown of biomass to sugars and cofermentation of sugars via new biological systems. These processes will have enhanced substrate range, temperature and inhibitor tolerance, and the capability to function in complex biorefining environments and over time scales that are economically viable.

The systems-integration phase, within 15 years, will incorporate concurrently engineered energy crops and biorefineries tailored for specific agroecosystems. Employing new and improved enzymes for breaking biomass down to sugars as well as robust fermentation processes jointly consolidated into plants or microbes, these highly integrated systems will accelerate and simplify the end-to-end production of fuel ethanol. In many ways, these final-phase technologies will strive to approach theoretical conversion limits. The new generation of biotechnologies will spur engineering of flexible biorefineries operable in different agricultural regions of the country and the world.

The success of this program for effectively converting cellulosic biomass to ethanol will be based on coupling sophisticated engineering with fundamental biological research. The new generation of biological research—systems biology—is built on the national investment in genomics. Systems biology involves new technologies for increasingly detailed high-throughput analyses and computing to make transparent the complexities of biology and allow predictive understanding and rational design. Multidisciplinary team research approaches will accelerate scientific progress and its translation to new biorefinery processes. Comprehensive suites of technologies, some in researchers' laboratories and some consolidated in facilities, will enhance technical performance, improve productivity, and reduce costs to allow affordable and timely progress toward these goals. New research capabilities and facilities will serve as an engine for fundamental research, technology development, and commercialization.